Management of thermal and mechanic flow characteristics in the output channels of a turbocharger centrifugal compressor

5th International Workshop on Heat/Mass Transfer Advances
for Energy Conservation and Pollution Control
August 13-16, 2019, Novosibirsk, Russia

Management of thermal and mechanic flow characteristics in the output channels of a turbocharger centrifugal compressor

L V Plotnikov[1], B P Zhilkin[1] and Yu M Brodov[1]

[1]Ural Federal University named after the first President of Russia B.N.Yeltsin, Mira str. 19, Ekaterinburg 620002, Russia

E-mail: plotnikovlv@mail.ru

Abstract. It is known that the thermal and mechanical characteristics of the air flow in the output channel of a turbocharger compressor largely determine the effectiveness of the gas exchange processes quality of a piston engine. The studies were carried out on an experimental installation containing a turbocharger, output channels of different configurations, a measuring base, and a data collection system. It was found that stabilization of the flow in the compressor output channel leads to a significant increase in heat transfer intensity (up to 25 %) compared to the baseline pipeline while simultaneously reducing the turbulence number by up to 30 %. A more significant increase in heat transfer intensity (up to 30 %) was observed in the output channel of the compressor with grooves compared to the base channel while simultaneously increasing the turbulence number by up to 12 %. The proposed configuration of the output channels of the compressor can be used to intensify heat transfer for the natural cooling of the air during the intake process. The configuration with a leveling grid can be used to stabilize the gas-dynamic flow parameters in order to reduce the hydraulic resistance of the intake system of a turbocharged engine.

1. Introduction

One of the main trends in the development of internal combustion engines (ICE) is to increase power and efficiency while maintaining mass and dimensional parameters. An effective solution to this problem is to install a turbocharger (TC) on the engine. It is known that the thermal and mechanical characteristics of the gas flows in the TC compressor output channel largely determine the quality of the gas exchange processes, the efficiency of the turbocharger and the piston engine [1-3]. Analysis of the results of modern research in the field of gas flows heat exchange in turbocharging systems indicates the relevance and great interest of specialists to this subject. Below, the works are noted, in which the influence of the configuration of inlet and outlet channels of a centrifugal compressor on its efficiency was studied based on mathematical modeling of gas-dynamics and heat transfer (in stationary and non-stationary conditions) [4, 5]. Deng et al. [6] and Leufvén et al. [7] developed mathematical models of TC (taking into account the mutual influence of the compressor and the turbine on each other) in order to simulate gas dynamics and heat transfer, as well as assess the efficiency of the turbocharger. There are also experimental works on this topic. The influence of different configurations of the compressor input devices on its performance, as well as on the noise level and safety margin was evaluated in the article [8]. Hirano et al. [9] and Gancedo et al. [10] investigated the gas dynamics and heat transfer flows in the input and output channels for different types of TC centrifugal compressors in order to increase their efficiency. Another article is devoted to the experimental study of the flow structure in the TC compressor wheel and the output channel using the PIV method [11]. Besides, there are some works on the comprehensive improvement of the configurations of intake and exhaust systems, TC operating modes and features of piston ICEs aimed at increasing their efficiency [12-14].

At the same time, there are virtually no studies related to the development of methods for controlling the thermo-mechanics of the flows in the compressor output channel in order to increase the efficiency of the intake system for ICEs with TC. The purpose of this study is to obtain new data on the effect of the configuration of the centrifugal compressor output channel on the non-stationary thermal and mechanical characteristics of gas flows.

2. Experimental setup and measurement base

The studies were conducted on an experimental setup (Fig. 1), which contained the following main elements: a turbocharger (TKR6), a bearing lubrication system, a TC rotor speed control system, an output channel, a measuring channel, and an automated data collection and processing system.

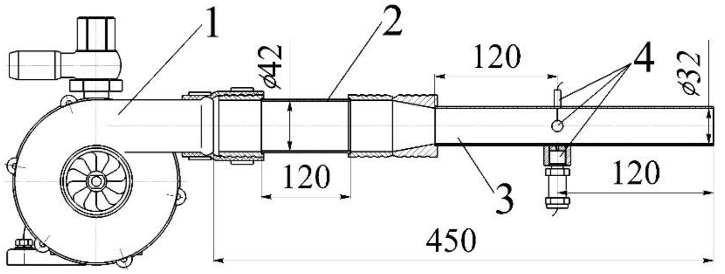

Figure 1. The main elements of the experimental setup: 1 – centrifugal compressor of the turbocharger; 2 – compressor output channel; 3 – measuring channel; 4 – installation sites for the thermo-anemometer sensor and pressure sensor.

The turbocharger consisted of a centrifugal compressor and a single-stage turbine. The TC rotor was rotated by supplying compressed air from an external source to the turbine blades. The variation range of the TC rotor rotational speed n_{TC} ranged from 10000 rpm to 60000 rpm. The gas temperature in the studied system was about 40-45 ^{o}C.

Measurements of the instantaneous values of the velocity and pressure of the air flow, as well as the local heat transfer coefficient and the TC rotor rotation frequency, were carried out in the course of the experiments. A digital contactless tachometer was used to measure the rotational speed of the TC rotor. A pressure sensor was used to measure the instantaneous values of the static pressure p_x in the flow after the compressor. The speed of the pressure sensor was less than 1 ms. A constant-temperature thermo-anemometer was used to determine the instantaneous values of the air flow rate w_x and the local heat transfer coefficient α_x. In our case, the sensitive element of the thermo-anemometer sensors was a nichrome filament with a diameter of 5 μm and a length of 5 mm. In this study, the determination of the local heat transfer coefficient in the gas flow is based on the idea of a heat transfer hydrodynamic analogy (Reynolds analogy). The analogy is based on the assumption of the unity of the processes of momentum and heat transfer in a turbulent flow and establishes a quantitative relationship between heat transfer and hydraulic resistance (Stanton criterion). The time constant of the thermo-anemometer was about 2 ms. The maximum systematic error in measuring the velocity wx was 5.4%, and the local heat transfer coefficient αx was 10.0%. A detailed description of the method for determining the local heat transfer coefficient and the calculation of experimental errors for this study are given in [15].

Straight, smooth pipe with a length of 120 mm and an internal diameter of 42 mm was used as the basic configuration of the compressor output channel. The leveling grid, according to the honeycomb principle, was installed in the pipe under consideration in order to stabilize the flow (Fig. 2, *a*). For another channel configuration, grooves were made on the inner surface of the pipe in order to intensify heat exchange (Fig. 2, *b*). At the same time, the length and inner diameter of the compressor output channel remained unchanged.

The efficiency of the studied configurations was estimated by a number of parameters: flow turbulence number, heat transfer intensity, average pressure, flow characteristics.

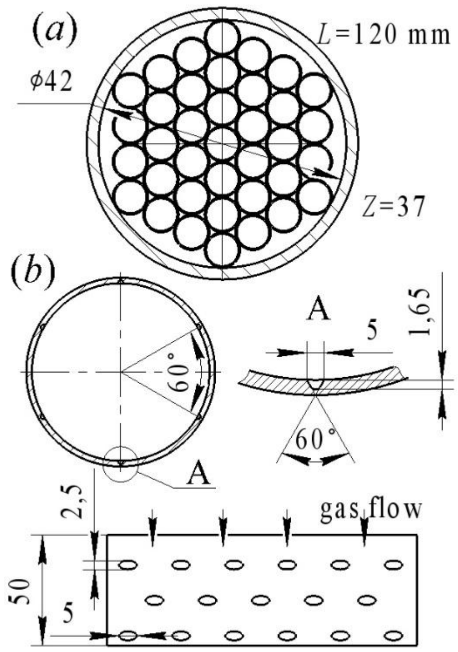

Figure 2. Configurations of the turbocharger compressor output channels: a – channel with leveling grid (honeycomb); b – channel with grooves.

3. Analysis of experimental results

The instantaneous values of flow rates and local heat transfer coefficients in time for three different configurations of the compressor output channel at the rotor TC rotation frequency equal to 10000 rpm are shown in Fig. 3

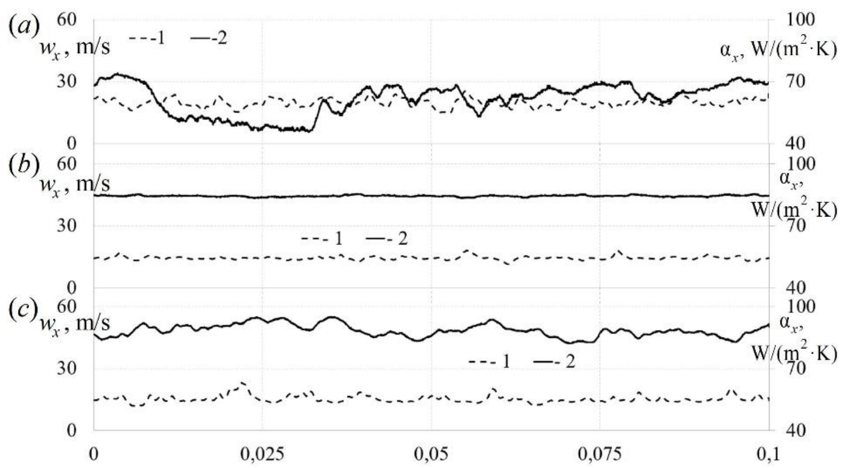

Figure 3. Dependences of air flow rate w_x (1) and local heat transfer coefficient α_x (2) on time in the compressor output channel of different configurations (n_{TC} = 10 000 rpm): a – base channel; b – channel with leveling grid; c – channel with grooves.

From Fig. 3, *a* it can be seen that significant amplitudes of air flow velocity pulsations are observed in the basic output channel of the compressor (standard deviation is 2.03). These pulsations are the result of the operation of the centrifugal compressor blades [16].

As expected, the installation of the leveling grid in the compressor output channel leads to a significant smoothing of the amplitudes of the velocity pulsations and the local heat transfer coefficient (Fig. 3, *b*). The standard deviation from the average velocity is 0.858. It can also be noted that there is a noticeable increase in the local heat transfer coefficient in the output channel with a leveling grid by about 25 %. The presence of grooves in the compressor output channel causes a noticeable increase in the local heat transfer coefficient by almost 30 % (compared to the base output channel); at the same time a slight smoothing of the amplitudes of the flow rate pulsations is observed (Fig. 3, *c*). The standard deviation from the average speed is 1.77. The results obtained in this study are in good agreement with those of other authors [17, 18]. It is known that various grooves and holes on the surface of pipelines lead to a significant intensification of heat exchange with a slight increase in the hydraulic resistance of the system.

The influence of the configuration of the compressor output channel on the turbulence number Tu can be seen in Fig. 4. The figure shows that the greatest differences in Tu are observed low and medium TC rotor speeds (from 10 000 to 40 000 rpm). For example, the turbulence number is reduced by almost 30 % when installing the leveling grid in the output channel (at n_{TC} = 10 000 rpm) compared to the base channel, and this difference does not exceed 15% at n_{TC} = 40 000 rpm. According to the authors, flow stabilization is associated with the equalization of the velocity field in honeycomb, i.e. the flow is stabilized after the impact of the compressor blades on it.

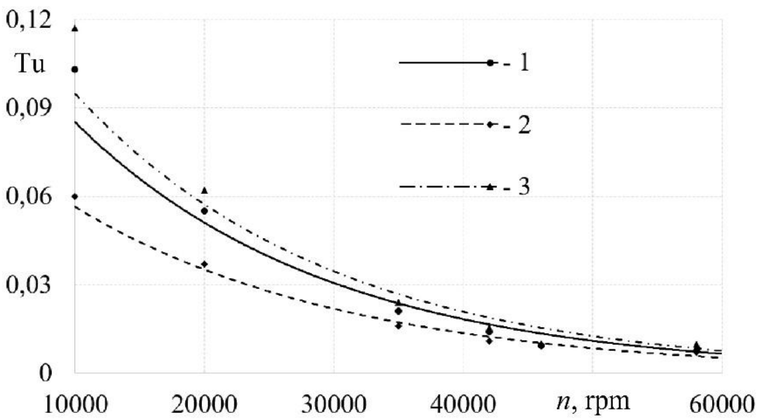

Figure 4. Dependences of the turbulence number Tu on the turbocharger rotor speed n_{TC} in the compressor output channel of different configurations: 1 – base channel; 2 – channel with leveling grid (honeycomb); 3 – channel with grooves.

The presence of grooves in the compressor output channel leads to an increase in the turbulence number by 9-12% compared to the base channel. According to the authors, this is due to the formation of vortices behind the grooves and the general turbulization of the flow.

It should be noted that the air flow rate through the output channel of the compressor remained virtually unchanged (within the experimental error – 5.5%) with all channel configurations at a certain fixed rotational speed of the rotor TC.

The effect of different gas-dynamic conditions in the output channels of different configurations on the local heat transfer coefficient is shown in Fig. 5.

The figure shows that the installation of a leveling grid and the presence of grooves in the compressor output channel lead to an intensification of heat exchange in comparison with the base channel. Intensification is observed at all TC rotor rotation frequencies. At the same time, the installation of a leveling grid in the output channel causes an increase in the local heat transfer coefficient by 13-25 %, and the presence of grooves – by 15-30 %. The greatest differences (20-30%) are observed at low rotor TC rotation frequencies n_{TC} (no more than 20000 rpm). It should be noted that the physical mechanism of heat transfer intensification for different configurations of the compressor output channel is different. In the case of the output channel with grooves, it consists in the formation of very significant secondary flow rates generated by the grooves [17, 18]. In turn, the leveling grid in the compressor output channel stabilizes the flow and contributes to the formation of a stable boundary layer with a corresponding intensification of heat transfer between the flow core and the channel walls.

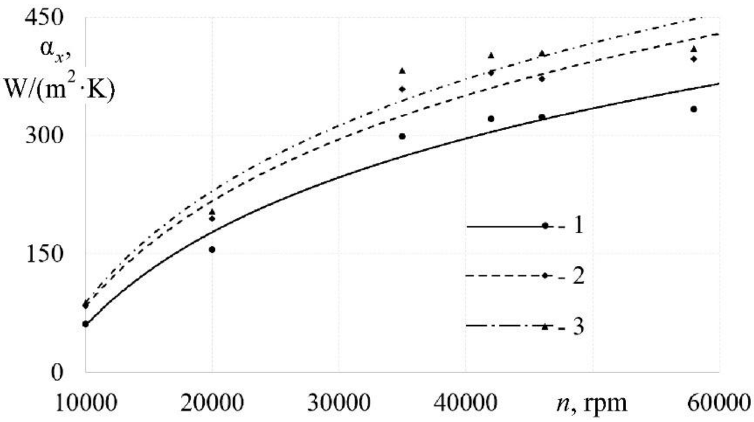

Figure 5. Dependences of the local heat transfer coefficient α_x on the turbocharger rotor speed n_{TC} in the compressor output channel of different configurations: 1 – base channel; 2 – channel with leveling grid (honeycomb); 3 – channel with grooves.

The obtained results can have a positive impact on the operation of turbocharged internal combustion engines since the intensification of heat exchange will provide natural cooling of the air in the intake system of the engine without increasing the hydraulic resistance.

4. Conclusion

Based on the study, the following main conclusions can be drawn.

1. It has been established that installation of a leveling grid in the output channel of the TK compressor results in:

- a decrease in the amplitude of the velocity pulsations by 2-3 times and a decrease in the turbulence number up to 30% as compared to the base channel;
- intensification of heat transfer in the channel by 13-25% compared to the base channel.

2. It is shown that the presence of grooves in the output channel of the TC compressor leads to:

- an increase in the turbulence number by 9-12 % compared to the base channel;
- growth of the local heat transfer coefficient up to 30 % compared to the base channel.

3. The obtained data expands the knowledge base on the influence of the configuration of the output channel of a centrifugal compressor on the thermal and mechanical characteristics of gas flows. These data can be used to design promising intake systems for turbocharged piston engines.

Acknowledgments
The work has been supported by the Russian Science Foundation (grant No. 18-79-10003).

References

[1] Heywood J B 1988 *Internal combustion engine fundamentals* (New York: McGraw-Hill) p 458

[2] Romagnoli A, Manivannan A, Rajoo S, Chiong M S, Feneley A, Pesiridis A, Martinez-Botas R F 2017 *Renewable Sustainable En. Rev.* **79** 1442–1460
[3] Plotnikov L V 2017 *IOP Conf. Series: J. Phys* **899** 042008
[4] Zhang M, Zheng X 2018 *Appl. Therm. Eng.* **131** 933–946
[5] De Bellis V, Bontempo R 2018 *Energy* **142** 507–517
[6] Deng Q, Burke R D, Zhang Q, Pohorelsky L 2017 *J. Eng. Gas Turb. Power* **139(6)** 062603
[7] Leufvén O, Eriksson L 2016 *Int. J. Engine Res.* **17(2)** 153–168
[8] Galindo J, Tiseira A, Navarro R, Tarí D, Meano C M 2017 *Appl. Therm. Eng.* **110** 875–882
[9] Hirano T, Ogawa T, Yasui R, Tsujita H 2017 *J. Therm. Science* **26(1)** 11–17
[10] Gancedo M, Gutmark E, Guillou E 2016 *Exp. Fluids* **57(2)** 16
[11] Torregrosa A J, Broatch A, Pastor J V, García-Tíscar J, Sharma R K, Cheung R 2018 *Exp. Therm. Fluid Science* **99** 420–432
[12] Hou H, Wang L, Wang R, Yang Y 2017 *J. Therm. Science* **26(2)** 97–106
[13] Wang T J 2018 *J. Mech. Science Techn.* **32(7)** 3465–3472
[14] Bozza F, De Bellis V, Teodosio L 2017 *Int. J. Engine Res.* **18(8)** 810–823
[15] Plotnikov L V, Zhilkin B P 2017 *Int. J. Heat Mass Transfer* **115** 1182–1191
[16] Plotnikov L, Grigor'ev N, Kochev N 2019 *EPJ Web Conf.* **196** 00007
[17] Isaev S A, Leontiev A I, Kornev N V, Hassel E, Chudnovskii Y P 2015 *High Temp.* **53(3)** 375–386
[18] Isaev S A, Schelchkov A V, Leontiev A I, Baranov P A, Gulcova M E 2016 *Int. J. Heat Mass Transfer* **94** 426–448